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LARGE FRAME AIRCRAFT (LFA) FIRE FIGHTING VALIDATION

TCA/PCA Methodology Evaluation

George F. Hall
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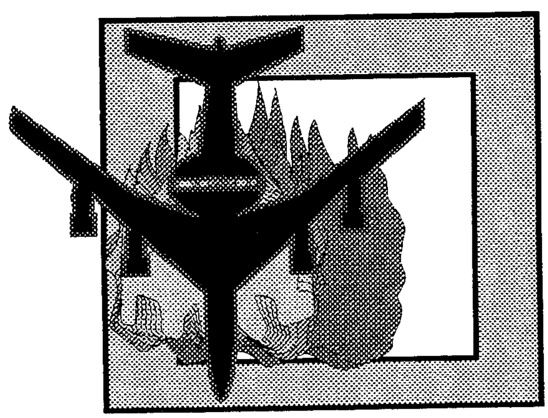
Final Report For The Period 1 December 1994 - 31 January 1995



January 1995

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This technical report has been reviewed and is approved for publication.

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13. ABSTRACT *(Maximum 200 words)*

This technical effort examines the technical and analytical basis of the National Fire Protection Association's (NFPA) methodology for determining minimum fire fighting agent quantities and flow rates for airport fire departments. The objective is to establish the validity of this methodology as representative of actual crash site conditions, and as an accurate means of estimating required agent quantities to effectively control and extinguish large frame aircraft (LFA) exterior and interior fires. The research consists of an analysis of past experimental program data, LFA crash statistics, recent Air Force fire department LFA crash experience, and NFPA 403 explanatory documents to determine TCA/PCA methodology areas of technical and operational weakness.

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PREFACE

This report was prepared by Alliance Fire Systems, Inc., 14 Poulas Court, Hampton, Virginia 23669, for the Wright Laboratory, Infrastructure Technology Section, Fire Research Group (WL/FIVCF), 139 Barnes Drive, Suite 2, Tyndall Air Force Base, Florida 32403-5323. The work was accomplished under Scientific and Technical Assistance (SETA) contract number F08635-93-C-0020.

This report presents the results of an analysis of NFPA 403, *Standard For Aircraft Rescue And Fire Fighting Services At Airports,* Theoretical and Practical Fire area (TCA/PCA) methodology for determining minimum agent quantities and flow rates for use by airport fire departments. Mr. Benjamin R. Partin and Dr. John H. Storm were the Principal Investigators. The WL/FIVCF Project Officer was Mr. George F. Hall. The analysis was conducted from 1 December 1994 to 31 January 1995.

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EXECUTIVE SUMMARY

A. INTRODUCTION

National Fire Protection Association (NFPA) 403, *Standard for Aircraft Rescue and Fire Fighting Services at Airports,* hereafter referred to as NFPA 403, is used by the Air Force and commercial fire departments to establish force structure policy for aircraft rescue and fire fighting (ARFF) capabilities. Statistics from 21 large frame aircraft (LFA) crash/fire incidents (Reference 40) indicate that airport fire departments, on average, used 4.9-times the agent quantities that are specified by NFPA 403 as being adequate for Airport Rescue and Fire Fighting (ARFF) operations.

B. OBJECTIVE

This technical effort examines the technical and analytical basis of the National Fire Protection Association's (NFPA) methodology for determining minimum fire fighting agent quantities and flow rates for airport fire departments. The objective is to establish the validity of this methodology as representative of actual crash site conditions, and as an accurate means of estimating required agent quantities to effectively control and extinguish large frame aircraft (LFA) exterior and interior fires.

C. BACKGROUND

1. NFPA 403, *Standard for Aircraft Rescue and Fire Fighting Services at Airports,* contains requirements for aircraft rescue and fire fighting (ARFF) services at airports. This standard defines the minimum extinguishing agent quantities and discharge rates for airport fire departments based on the largest size of aircraft to be protected. NFPA employs the Theoretical and Practical Critical Area (TCA/PCA) methodology to calculate extinguishing agent quantities and the flow rates required to establish and maintain fire control inside a "critical fire area" within an acceptable period of time. The size of this area, the flow rates of the agent to be applied, and the duration of agent application are based on the requirement to permit the safe evacuation of aircraft occupants.

2. The Air Force has aligned crash/fire rescue (CFR) vehicle assets for fire departments using the NFPA 403 standard. Agent quantities and flow rates vary according to the largest aircraft permanently assigned to the base. For air bases with assigned LFA, these aircraft can include B-

52, B-1 and B-2 long range bombers, C-141, C-5A and C-17 air mobility providers, and/or KC-135 and KC-10 air-to-air refuelers. Other, more specialized, LFA include the E-3A AWACS and E-4A/B airborne command post aircraft, as well as the Presidential LFA fleet (B-707/747). These aircraft, fundamentally, are irreplaceable military assets. Therefore, the Air Force must ensure that the minimum fire department crash vehicle and agents that are determined according to the NFPA 403 TCA/PCA methodology are capable and sufficient to minimize the loss of life and property under survivable LFA crash-fire conditions.

3. The NFPA 403 TCA/PCA methodology evolved during the 1960's and early 1970's. It was based, in part, on the operational experience of the international airport fire protection community at that time, and on limited live fire experimental data relating to crash-fire conditions and agent performance effectiveness. The basic methodology was not founded on personal LFA crash experience, LFA crash statistics or on experimental agent performance data based on accurate LFA crash site modeling.

4. The NFPA 403 formula that determines agent minimum required volumes has been administratively "adjusted" over the years to account for LFA fuel loads, new agents, passenger capacities and interior fire fighting requirements. No comprehensive tests have been conducted to clinically validate each element of adjustment or the entire TCA/PCA methodology using realistic crash site conditions, a full range of currently available agents and the crash worthiness of current LFA.

5. Air Force criteria to determine the required mix of vehicles and agent application flow rates to effectively deal with LFA fires are based on the NFPA 403 methodology for determining the Theoretical and Practical Critical Fire Areas (TCA/PCA). Minimum AFFF agent application flow rates (gpm/sq ft) to control TCA/PCA fires were determined from two-dimensional pit fire experiments. In these experiments static jet fuel pools were floated on a water surface, ignited and extinguished with AFFF. There are three fundamental flaws in this methodology: (1) Actual LFA accidents do not occur where all released fuel will be pooled on top of a water surface. LFA fires normally occur on graded concrete pavement surfaces or grass infield areas, or both. (2) Most LFA fires involve a dynamic, 3-dimensional, flowing fuel condition, where elevated, ruptured fuel cells continuously feed a fuel source to the pool fire below. (3) AFFF is not effective against three-dimensional flowing fuel fires.

6. Given these fundamental "built-in" inaccuracies, the Chief of Air Force Fire Protection established the formal requirement to:

a. Establish the analytical and experimental bases for improving the accuracy and validity of the NFPA 403 methodology that is used to determine airport minimum extinguishing agent quantities, agent discharge rates and ARFF vehicle and equipment configurations for LFA fire fighting and rescue operations.

b. Determine critical LFA crash site conditions and aircraft configurations that impact the success of ARFF operations.

c. Identify LFA-specific test parameters that can be incorporated into a live fire test program to experimentally validate fire fighting agent and delivery system performance under realistic LFA conditions.

The analytical and experimental program is being conducted by Wright Laboratory's Fire Research Group (WL/FIVCF) at Tyndall Air Force Base, Florida.

D. SCOPE

This research consists of an analysis of past experimental program data, LFA crash statistics, recent Air Force fire department LFA crash experience, and NFPA 403 explanatory documents to determine TCA/PCA methodology areas of technical and operational weakness.

E. TECHNICAL APPROACH

1. The technical or operational basis for each factor comprising the NFPA 403 TCA/PCA calculation for determining minimum agent quantities and flow rates for LFA was established. Data were obtained by literature review and by direct discussions with Captain B. Victor Hewes. He was the International Federation of Airline Pilots' Associations (IFALPA) representative to the 1970 and 1972 international panels that designed the TCA/PCA calculation process. Captain Hewes also is a member of the NFPA Technical Committee on Aircraft Rescue and Fire Fighting, which revised NFPA 403 in 1993 using the TCA/PCA methodology.

2. Reference documents that define the 1970's evolution of each component of the TCA/PCA methodology and the supporting historical data bases were reviewed. The technical relevance of each factor in the TCA/PCA calculation to accurately determine minimum LFA agent quantities and flow rates was established. This was done by direct comparison of each NFPA 403 TCA/PCA methodology parameter to its actual crash site counterpart condition.

Other factors considered included more recent experimentally-proven parameters of current extinguishing agent and crash vehicle performance, as well as LFA physical data, such as engine and fuel cell locations and air frame crash worthiness.

3. In the follow-on research (Reference 40), a large scale, live fire, experimental program is defined to determine the technical validity of the TCA/PCA methodology and to more accurately predict required minimum agent quantities. The experimental data will be used to quantify the magnitude of the errors inherent in the assumptions that govern the current NFPA 403 calculations. Additionally, the data can used to provide the basis for developing and validating a more realistic and accurate approach to predict agent for ARFF operational requirements.

F. CONCLUSIONS

1. The NFPA 403 TCA/PCA methodology is operationally and technically flawed, does not reflect current LFA crash site conditions, and will not accurately predict agent quantities for existing or next generation LFA. Specifically:

- The operational fire fighting experience and databases of the 1960's that contributed to a large measure of the current TCA/PCA calculational procedure did not include the on-scene experience, crash response histories and interior/exterior fire suppression statistics from modern LFA, such as the B-747, DC-10, L-1011, and Airbus A-300/340.

- Fire tests to determine agent performance and flow rates were conducted, primarily, using protein foam and "ideal" static, flat, 2-dimensional pool fire scenarios with the fuel column floated on water or on a paved surface. Today's Air Force and commercial airport incident site conditions include the use of Aqueous Film-Forming Foam (AFFF) and 3-dimensional flowing fuel conditions from damaged fuel lines/cells and a wide mix of sloped pavement, grass, sand, snow or ice surfaces.

- Test fires were limited, primarily, to the exterior area of the aircraft. Fuselage mockups were not realistic, and did not accurately account for the crash-worthiness or insulating properties of modern cabin interiors. Extinguishment of current-day interior combustible materials was not experimentally addressed.

2. The "largeness" of current inventory LFA creates difficult fire fighting and rescue problems and obstacles that were not present or identified when the original TCA/PCA methodology was being developed. These include:

- 3-dimensional, cascading fuel or pressurized hydraulic fluid fires originating in high T-tail engine nacelles, APUs or dry bay compartments and high-wing engine nacelles, dry bays and/or fuel cells.

- High, elevated, "hard to reach" sources of these 3-dimensional, flowing fuel fires, such as the interiors of engine nacelles, overhead wing dry bays, or APU/electronics equipment bays.

- The crash worthiness of new generation LFA results in larger, intact, post-incident aircraft components. Each may present a separate exterior and interior fire fighting and rescue requirement, to include inverted cabin sections. Extinguishing agent requirements for fires fueled by cabin interior panels, seat/cushion materials, composite materials and other interior combustibles have not been experimentally determined.

3. A revised methodology to calculate required agent quantities for airport fire fighting and rescue is required to ensure that the Air Force maintains the fire department manpower, vehicle, agent and equipment resources necessary to provide a defined and repeatable level of fire protection at air bases supporting LFA operations.

G. RECOMMENDATIONS

1. Wright Laboratories' Fire Research Group (WL/FIVCF) should conduct an experimental program to determine the margin of error inherent in the 1993 edition of NFPA 403 and the TCA/PCA methodology upon which this standard is founded. The live fire test program should be configured to generate the technical basis for more accurately predicting minimum agent quantities, delivery flow rates, and vehicle configuration requirements for airport fire departments.

2. WL/FIVCF should conduct large scale, live fire performance evaluation tests on CFR vehicles, equipment and agents. The effort should be designed to:

a. Identify improvements required to optimally deal with LFA interior and exterior 3-dimensional fires, and "hard to reach" fires, such as high nacelles and wing fuel cells, dry bays and upper crew/passenger compartments.

b. Quantify the extinguishment performance of candidate primary agents against LFA 3-dimensional fires.

c. Evaluate new agent delivery and control system performance under realistic LFA crash/fire test configurations.

H. APPLICATION

1. Analysis and experimental test results from this research can be applied by Air Force and commercial fire departments to force structure and training planning for LFA crash/rescue response. The current NFPA 403 TCA/PCA methodology does not realistically model LFA crash site conditions or the 3-dimensionality of survivable LFA crash fires. This information must be considered by Air Force and commercial fire chiefs in their determination of minimum agent quantities, agent flow rates and agent delivery vehicles and equipment that must be available at air bases and airports for LFA operations. Research results can also be employed to influence LFA pre-fire plans, and fire fighter training and educational programs.

2. Large scale, 3-dimensional flowing fuel live fire tests will be conducted during follow-on research to evaluate the relative extinguishment performance of AFFF, hydrochem (AFFF + dry chemical mixture) and dry chemical agents under realistic LFA crash/fire conditions. Additionally, new technology agent delivery systems that include articulating booms with penetrator and high-reach nozzles will be evaluated to determine their potential for improving LFA fire fighting operations. The results of these tests can be used by Air Force and commercial fire departments to design and purchase new agent delivery apparatus and to select the best primary and secondary agents for LFA crash/fire response.

I. BENEFITS

This research will enable Air Force and civilian fire chiefs to more accurately estimate LFA crash site conditions and to better specify the mix of fire extinguishing agents and delivery equipment needed for optimum fire fighting and rescue operations. Research results will enable safer and more effective ARFF operations, and should result in lower fire and loss of life statistics for survivable LFA crash incidents.

J. TRANSFERABILITY OF TECHNOLOGY

Research results are transferable to fire departments and fire educational programs, worldwide. Findings and recommendations should be submitted to the NFPA, the Federal Aviation Administration (FAA) and ICAO for their consideration to formally modify the TCA/PCA methodology for determining minimum required agent quantities and flow rates, based on analysis and live fire experimental test results.

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INTRODUCTION

A. OBJECTIVE

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D. SCOPE

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E. DOCUMENT ORGANIZATION

1. Section II documents a literature review to determine key factors that can impact the success of fire fighting and rescue operations at survivable LFA crash sites. Documents were reviewed for information on LFA exterior fires and interior cabin fires, and for explanatory material regarding the development of the NFPA 403 TCA/PCA methodology. In Section III, the NFPA 403 TCA/PCA methodology for determining minimum airport requirements for primary extinguishing agents is described. The Air Force assigns CFR vehicle assets to fire departments, based on aircraft size and NFPA 403 primary agent requirements. This correlation also is discussed in Section III.

2. Section IV contains the results of an analysis of each calculational variable contained in the NFPA 403 TCA/PCA equation for Airport Category 9 aircraft. In Section V, aircraft-specific factors, such as size and compartmentization, as well as agents and agent delivery systems are discussed with respect to their impact on fire department ARFF capabilities and extinguishment success.

3. Section VI contains the description and objectives for a test program to experimentally validate critical elements of the NFPA 403 TCA/PCA equation for determining ARFF operation minimum agent requirements. Section VI also defines a large-scale test program for 3-dimensional fire fighting agents and new technology agent delivery systems that have the potential to enhance LFA fire fighting effectiveness. The report's summary, conclusions and recommendations are contained in Section VII.

SECTION II

TECHNICAL APPROACH

A. DOCUMENT REVIEW

The following documents were reviewed to determine the historical and technical basis of the NFPA 403 TCA/PCA methodology for determining minimum airport requirements for agent quantities and crash vehicle agent flow rates.

1. Airport Emergency Service Standards

U.S. national and international standards have been established to provide a consistent basis for establishing airport fire fighting and rescue emergency response services. Although minimum agent quantities and flow rates may be different, each uses the TCA/PCA methodology as the basis for determining these requirements. The primary, internationally-recognized standards are:

- United States Federal Aviation Administration (FAA): Advisory Circular No. 150/5210-6C, *Aircraft Fire and Rescue Facilities and Extinguishing Agents,* 1/28/85.

- International Civil Aviation Organization (ICAO): Annex 14, Volume I, *Aerodrome Design And Operations,* Chapter 9, July 1990.

- National Fire Protection Association (NFPA): NFPA 403, *Standard for Aircraft Rescue and Fire Fighting Services at Airports*, 1993.

2. NFPA 403 Explanatory Material

a. NFPA 403, Appendix A, Explanatory Material, provides the historical genealogy of the TCA/PCA methodology, from its inception in 1970 to its current form. Appendix A references the organizational proceedings and technical reports that were considered by the NFPA Technical Committee in defining agent and flow rate quantities, as specified in the 1993 edition of the standard.

b. NFPA 403 TCA/PCA methodology explanatory documents reviewed were:

- Hewes, B.V., Chairman, "Report of the First Meeting of the ICAO Rescue and Fire Fighting Panel (RFFP-I)," March 10-20, 1970, Montreal, Canada.

- Geyer, G.B., "Evaluation of Aircraft Ground Fire Fighting Agents and Techniques," AGFSRS-71-1, Wright-Patterson AFB, OH, February 1972.

- Harley, R.A., Chairman, "Report of the Second Meeting of the ICAO Rescue and Fire Fighting Panel (RFFP-II)," June 5-16, 1972, Montreal, Canada.

- Ansart, F., Analysis Reports of Accidents No. 1 to 217 Filed with ICAO as of March 1970. Unpublished meeting records of reference material used by RFFP-II.

3. Other Relevant Technical Documents

a. The original TCA/PCA methodology was developed in the 1970-1972 time frame. It was based on crash experience and experimental data available at that time, and did not include statistics from current generation LFA suppression and rescue incidents. Since then, a significant database of commercial and military LFA crashes and ground-initiated incidents involving wide-body LFAs has been established. Additionally, experimental live fire research programs have been conducted by the Air Force and FAA on vehicle and agent performance and other aircraft crash survivability factors that were not available to the original architects of the TCA/PCA methodology.

b. Information relevant to the applicability of the TCA/PCA methodology to current crash and ground-initiated fire suppression and recue operations is contained in the following documents:

- Hewes, B.V., "Petition For The Revision of A.C. 150/5310-6C (FAA Advisory Circular) and FAR Part 139," July 1991.

- Sarkos, C.P., "FAA's Cabin Fire Safety Program: Status and Recent Findings", FAA Paper, 1990.

- Cohn, B.M. & Campbell, J.A., "Minimum NeedsFor Airport Fire Fighting and Rescue Services", FAA-AS-71-1, January 1971.

- Geyer, G.B., Comparative Evaluation of Fire Fighting Foam Agents, FAA-RD-79-61, 1979.

- Geyer, G.B., "Equivalency Evaluation of Fire Fighting Agents And Minimum Requirements At Air Force Airfields", DOT/FAA/CT-82/109, 1982.

- EASAMS Ltd. "Aerodrome Fire And rescue Services", Civilian Aviation Authority Reference No. DORA Report 7201, London, May 1972.

- Risinger, C.W., Pike, H.A., Casey, R.J., & Supinski, M.. "*Large Frame Aircraft (LFA) Firefighting Analysis*", Volume I-III, <u>ESL TR-92-77</u>, Air Force Engineering And Services Laboratory, Tyndall AFB, FL, March 1993.

- Hewes, B.V., "Agent Quantity Re-Evaluation", Personal Paper Prepared For ARA SSG Subtask 3.09, Technical Analysis and Evaluation, Task: Theoretical and Practical Critical Fire Areas (TCA/PCA) Analysis, January 1995.

4. Air Force Policy Documents

a. The United States Air Force (Air Force) has aligned ARFF vehicle assets using the 1993 Edition of NFPA 403 as the standard. The methodology for calculating agent quantities in NFPA 403 is interpolated to Air Force flying operations, according to the largest military aircraft stationed at each location. For LFA, these are B-52, B-1 and B-2 long-range bomber aircraft, C-141, C-17 and C-5A air mobility providers, and/or KC-135 and KC-10 air-to-air refuelers. Other, more specialized LFA include the E-3A AWACS and the E-4A/B airborne command post aircraft.

b. The Air Force establishes specific ARFF vehicle sets at each LFA installation, based on the Air Force crash/fire rescue (CFR) mission requirements of assigned aircraft. Direction for Air Force CFR vehicle sets is contained in Table of Allowances (TA) 012.

B. DESCRIPTION OF THE NFPA 403 TCA/PCA METHODOLOGY

The purpose and specific mathematical calculations of the NFPA standard are defined. As an example, the methodology is applied to a B-747-200 LFA to determine agent and flow rate quantities for NFPA Category 9 airports. Air Force Fire Protection vehicle agent quantities, flow rate and resupply capabilities, as defined in TA 012, are compared to these minimum NFPA requirements.

C. NFPA 403 TCA/PCA METHODOLOGY CRITICAL EVALUATION

1. Each specific variable in the NFPA 403 methodology for determining minimum agent quantities and flow rates is examined on the basis of:

- The technical or practical experience basis of the factor, as determined by the results of the literature review.

- More recent/current experimental data regarding fire fighting agent performance effectiveness and aircraft cabin crash-worthiness.

- The relevance to actual crash and ground-initiated site conditions, as determined by the author's professional experience and by LFA crash report data.

2. For each variable, the impacts of the differences between the NFPA 403 TCA/PCA methodology and actual site conditions or more relevant experimental data are established. These differences are then used to assess the relative effectiveness of the TCA/PCA methodology to predict crash fire areas and to generate minimum agent quantities that are operationally sufficient to deal with future Air Force LFA incidents.

D. IMPACT OF CURRENT TECHNOLOGY AIRCRAFT AND FIRE SUPPRESSION AGENTS AND EQUIPMENT ON AIRPORT FIRE DEPARTMENT CRASH-RESCUE CAPABILITIES

1. The NFPA 403 TCA/PCA methodology for determining minimum requirements for agent quantities and flow rates was established in the early 1970s and was based on the operational and experimental experience at that time. In general, the largest aircraft of that era were in the B-707 and B-52 classes, and operational fire extinguishment experience was based on the use of protein foam.

2. Since then, commercial and military LFA have grown substantially in size and in passenger and fuel capacities, the crash worthiness of LFA has improved, Aqueous Film-Forming Foam (AFFF) is now widely used by Air Force and commercial airport fire departments, and more capable crash vehicle agent delivery technologies are available for application to CFR incident scenarios. The impacts of these factors on crash fire geometries, site conditions and fire suppression operations are identified and evaluated. Results are employed as an additional basis for evaluating NFPA 403 TCA/PCA methodology relevancy to current Air Force operational requirements.

SECTION III

DESCRIPTION OF THE NFPA 403 TCA/PCA METHODOLOGY FOR DETERMINING AIRPORT MINIMUM AGENT REQUIREMENTS

A. PURPOSE AND INTENT

1. The primary objective of Air Force and airport fire services is to save lives. An additional Air Force objective is to limit the damage to military operational assets, which are uninsured and, fundamentally, irreplaceable at this time.

2. Within this framework, the NFPA 403 TCA/PCA methodology is founded on the concept of a "critical fire area" that must be controlled, in order to permit the safe evacuation of occupants. As defined in Appendix A of the standard, the purpose of the methodology is to:

- Provide a consistent method to estimate crash site critical fire areas based on aircraft dimensions.

- Specify the minimum requirements for fire extinguishing agent quantities and agent flow rates, as well as the number of vehicles needed to effectively control the critical fire area and permit aircraft occupant egress or rescue.

3. The intent of the standard is to define the minimum adequate resources for initial fire response to permit occupant survivability and rescue before reinforcements arrive and agent resuppy is established.

4. NFPA 403 is not intended to predict the total amount of agent gallonage that may be required for the full extinguishment of every aircraft fire.

B. NFPA 403 TCA/PCA METHODOLOGY SUMMARY

1. Critical Fire Area Definitions

   - **Theoretical Critical Area (TCA):** The fire area adjacent to the aircraft that must be controlled to ensure temporary fuselage integrity and to provide an occupant escape area.

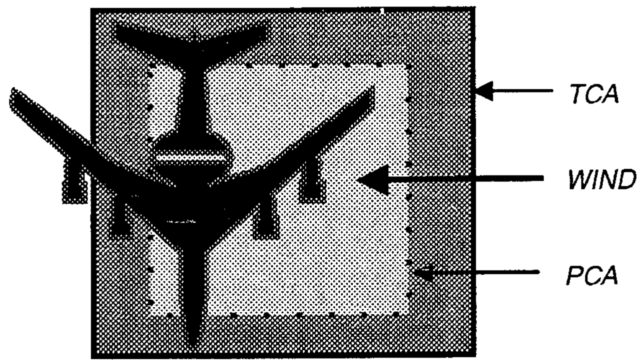

Figure III-1. Theoretical and Practical Fire Areas

- **Practical Critical Area (PCA):** The area used to calculate minimum agent quantities and flow rates. The PCA is defined as 2/3 of the size of the TCA, as determined by the ICAO RFFP-II committee.

2. TCA/PCA Calculation for NFPA 403 Airport Category 9 LFA

TCA = L X [W + 98]

PCA = 2/3 X TCA

where: L = Fuselage Length in Feet

W = Fuselage Width in Feet

3. Minimum Required Agent Quantities

$$\mathbf{Q = Q_1 + Q_2 + Q_3}$$

where:

Q = the minimum gallons of AFFF required to control PCA and interior cabin fires to enable occupant rescue before the arrival of backup forces. Q may or may not be sufficient to extinguish all external and internal fire areas.

Q_1 = the gallons of AFFF required to control the PCA for 60 seconds.
Q_2 = the gallons of AFFF required to maintain PCA fire control to complete rescue operations prior to the arrival of backup forces or the establishment of agent resupply.

Q_3 = the gallons of agent required for interior LFA fire fighting.

Explicitly:

Q_1 = PCA X 0.13 GPM/SF X 1 minute

Where 0.13 GPM/SF = the specified application rate for AFFF extinguishment of jet fuel pool fires.

Q_2 = 1.7 Q_1

Where 1.7 is an empirical factor to account for the size, fuel loading and passenger capacity of Airport Category 9 LFA.

Q_3 = 250 GPM X 10 minutes = 2,500 gallons

4. Agent Quantities Based on a B-747-200 LFA (Airport Category 9)

a. Computational Method

L = 231 feet, W =21.4 feet

Therefore:

TCA = [231 X (98+ 21.4)] = 27,581 square feet

PCA = 2/3 X 27,581 = 18,388 square feet

Q_1 = 18,388 SF X 0.13 GPM/SF X 1 minute = 2,390 gallons

Q_2 = 1.7 X 2,390 = 4,063 gallons

Q_3 = 2,500 gallons

and, **Q = 8,953 gallons**

*Additionally, the minimum required agent flow rate is **Q_1 gallons in 1 minute or 2,390 GPM.***

b. NFPA 403, Table 3-3.1 (a), Minimum Extinguishing Agent Quantities and Discharge Rates, rounds these values to 9,000 gallons and 2,400 GPM, respectively, rate for Category 9 airports.

C. APPLICATION OF NFPA 403 TO THE AIR FORCE TABLE OF ALLOWANCE (TA-012) FOR CRASH/FIRE RESCUE (CFR) VEHICLE EQUIPMENT ASSETS

1. Air Force vehicle sets are defined at Table III-1. Each set configuration determines the total combined agent gallonage and agent delivery flow rate available for initial response at a CFR incident site.

2. Air Force vehicle sets also include agent tanker allowances for 5,000 gallons of initial, on-board resupply, which is not specified in NFPA 403. Additionally, TA 012 specifies that a 100 percent water replenishment supply must be available, once hydrant lines are established.

3. For Air Force TA 012 Set 3 bases (LFA<175 feet in length), 9,000 gallons of on-board vehicle agent are required. This set is designed to protect aircraft that are equivalent in size to those specified in NFPA 403 Airport Category 9.

4. For Air Force TA 012, Set 4 bases (LFA>175 feet in length), 12,000 gallons of agent are established. This set is designed to protect aircraft that are equivalent in size to those specified in NFPA 403 Airport Category 10.

Table III-1. Air Force CFR Vehicle Set 3 And Set 4 Agent Gallonage Comparison

CFR VEHICLE GALLONAGE	**P-19*** **1000 GAL**	**P-26**** **5000 GAL** No. Vehicles/ Gal Per Vehicle	**P-23***** **3000 (GAL)** No. Vehicles/ Gal Per Vehicle	**Air Force TOTAL GALLONS** (Initial Response)
1994 Set #3	0/0	1/5,000	4/3,000	12,000
1995 Set #3 (Aircraft <175' L)	1/1,000	1/5,000	3/3,000	9,000
1995 Set #4 (Aircraft >175' L)	1/1,000	1/5,000	4/3,000	12,000

* For contingencies & training only.
** For resupply only.
*** For ARFF initial response.

SECTION IV

NFPA 403 TCA/PCA METHODOLOGY CRITICAL EVALUATION

A. DEFINITION OF VARIABLES

Figure IV-1 depicts the total NFPA 403 calculation for determining the minimum quantity of AFFF extinguishing agent, Q, required for Airport Category 9 LFA. The definition of each factor is also included in the figure.

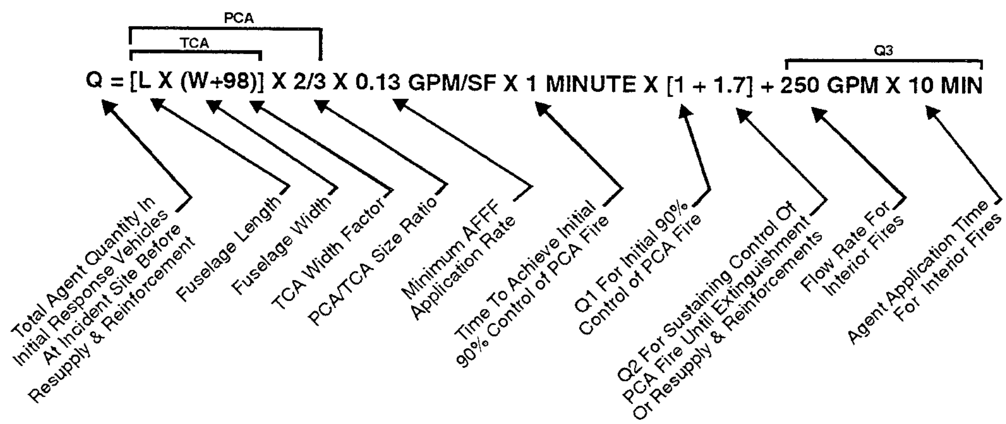

Figure IV-1. Definition of Minimum Agent Quantity Calculational Variables

B. CRITICAL EVALUATION

1. Approach

The following are established for each NFPA 403 TCA/PCA methodology variable/factor defined in Figure 2 for Airport Category 9 LFA:

- The analytical or experimental basis for the variable, as determined by the 1970 RFFP-I and 1972 RFFP-II reports and the NFPA 403 Appendix A commentary and cited literature references.

- The relevance of each variable to actual crash/incident site conditions and to more recent live fire test data, as determined by LFA crash statistics and FAA/Air Force experimental programs.

Where significant differences between the assumed NFPA 403 calculational variable assumptions and actual site conditions and/or more relevant experimental data are identified, the impacts of these differences are discussed.

2. Critical Evaluation of Each NFPA 403 Calculational Factor For LFA

a. TCA Length = Fuselage Length (L)

(1) *Analytical/Technical Basis.* An auditable, consistent estimate of TCA length. Determined unanimously by RFFP-I panel members. In general, the fire area created by a crash or ground-generated accident/incident will vary as a function of the fuel capacity of the aircraft. This area, in turn, is determined by aircraft overall size, of which the length is a primary factor.

(2) *Relevance to Actual Crash Site Conditions or Recent Live Fire Experimental Data.* None. Based on fire areas experimentally generated by FAA fuel spills on water and flat concrete surfaces (Reference 23). Provides a convenient and consistent estimate of one assumed TCA dimension, i.e., length. Does not accurately predict any dimension of an actual crash site fuel spill or fire area. Does not account for the horizontal dispersion and runoff of fuel on sloped pavement or soil surface conditions, or the vertical assimilation of the fuel into the ground due to ambient soil permeability and saturation conditions.

(3) *Impacts on NFPA 403 TCA/PCA Methodology To Accurately Predict Minimum Required Agent Quantities and Flow Rates.* Significant impacts on methodology accuracy. A convenient method to empirically relate relative aircraft fuel capacities via size (length) to assumed crash fire areas. As a single element in the total NFPA 403 TCA/PCA methodology, it provides no experimental or statistical validity to the calculational basis for Q.

b. Fuselage Width (W)

(1) *Analytical/Technical Basis.* Actual measurement of fuselage width. Used by the RFFP-II panel as a component of the estimate for the TCA width.

(2) *Relevance to Actual Crash Site Conditions or Recent Live Fire Experimental Data.* None. It is an auditable and consistent measurement of aircraft width.

(3) *Impacts on NFPA 403 TCA/PCA Methodology To Accurately Predict Minimum Required Agent Quantities and Flow Rates.* None. It is a component of the empirical factor used by NFPA 403 to estimate TCA width. Deficiencies/impacts of the TCA width estimate are discussed in the next subparagraph.

c. TCA Width = W + 98

(1) *Analytical/Technical Basis.* The RFFP-II estimate for TCA width was W + 100 feet. The 100-foot distance is an experimentally-determined standoff dimension (Reference 23) that is judged to:

- Prevent life-threatening interior heat buildup conditions for intact cabin sections

- Provide a reasonably safe rescue corridor for aircraft occupants.

The 1993 Edition of NFPA 403 has changed this dimension to (W + K) feet. The "K" factor varies from 39 feet to 98 feet, according to the size of the aircraft. 98 feet is used for Airport Category 5, and above aircraft. FAA Advisory Circular 150/5210-6C, Reference 37, uses W + 100 feet for the TCA width. No technical references are cited by NFPA 403 to explain the technical relevancy of the "K" factor. Experimental data on human fire exposure thresholds (Reference 30) indicate that the minimum distance from a flame front is 60-feet, assuming the travel distance from the aircraft to safety is 50-feet long. This would equate to a minimum TCA width of (W + 120)-feet, to permit the safe egress from both sides of an aircraft fuselage section involved in fire.

(2) *Relevance to Actual Crash Site Conditions or Recent Live Fire Experimental Data.* None. Does not accurately predict TCA width. Does not account for the horizontal dispersion and runoff of fuel on sloped pavement or soil surface conditions, or the vertical assimilation of the fuel into the ground due to ambient soil permeability and saturation conditions. The factor (W + 98) provides a survivable emergency egress pathway, only if occupant egress is conducted from the upwind side of the aircraft where a 60-foot or greater distance from the TCA flame front can be maintained.

(3) *Impacts on NFPA 403 TCA/PCA Methodology To Accurately Predict Minimum Required Agent Quantities and Flow Rates.* As a single element in the total NFPA 403 TCA/PCA methodology, it provides no experimental or statistical validity to the calculational basis for Q.

d. Theoretical Critical Area (TCA) = L X (W + 98)

(1) *Analytical/Technical Basis.* This mathematical relationship has not been analytically or experimentally validated as a means to accurately predict

actual fuel pool sizes that result from survivable crash-fires of LFA or ground initiated incident. The term was derived from Air Force research (Reference 23) defines the TCA as "the area adjacent to the fuselage extending outward in all directions to those points beyond which a large fuel fire would not melt an aluminum fuselage, regardless of the duration of the fire exposure time."

(2) *Relevance to Actual Crash Site Conditions or Recent Live Fire Experimental Data.* None.

a Actual incident site fuel fire areas are determined by the magnitude (GPM) and location (s) of the fuel being spilled/leaked, and the surface and gradient conditions of the soil or pavement upon which the fuel impinges. Actual LFA fires can consist of 2-dimensional pool fires that are constantly replenished by 3-dimensional running fuel fires. The Air Force reported (Reference 23) that the TCA "is not intended to represent the average, maximum or minimum spill fire size associated with a particular aircraft."

b The TCA underestimates a very serious LFA crash-fire condition: a post-incident fire area along the entire length of the fuselage and extending outward on both sides for a distance of 50 feet. The fire fighting requirement in this case is to provide sufficient CFR vehicles and agent to prevent passenger exposure to non-survivable conditions along an exterior escape corridor. Therefore, according to the Reference 30 passenger survivability data, the fire area to be controlled would be [L X (W + 120)] square feet. For a B-747 aircraft, the use of W + 98 versus W + 120 in the TCA equation yields a fire area that is 16 percent smaller than Reference 30 states is required for safe passenger egress from both sides of the aircraft.

(3) *Impacts on NFPA 403 TCA/PCA Methodology To Accurately Predict Minimum Required Agent Quantities and Flow Rates.* The TCA does not predict actual fuel release pool sizes or 3-dimensional fuel column release rates. The TCA is a consistent measurement than can be statistically compared to actual fire areas from LFA accident report data (See next factor discussion).

e. PCA/TCA Size Ratio = 2/3

(1) *Analytical/Technical Basis.* This factor reduces the TCA by 1/3 to form the PCA. The PCA is then used to determine minimum agent quantities and flow rates. The RFFP-II panel cites the Ansart report of commercial crashes as of March 1970 (Reference 32) as the basis for this determination. The Panel erroneously concluded that "the actual amount of water for foam had been compared with

the amounts recommended by RFFP-I (i.e. the TCA) and it had been found out that of 106 accidents for which this information was available, in 99 cases or 93 percent the amounts recommended by the Panel were in excess of those required in the actual aircraft accident." There are no data in the Ansart Report to support this conclusion.

(2) *Relevance to Actual Crash Site Conditions or Recent Live Fire Experimental Data*. None.

a The Ansart report has been thoroughly reviewed during this technical effort. There are no data on actual fire areas or fire area comparisons to computed TCA's. Furthermore, the largest aircraft for which crash statistics are provided are in Airport Category 6 (B-737-size aircraft). The Ansart report provides no crash fire statistics for aircraft in the LFA category, as defined in this analysis (B-747, C-5A, C-17, etc.).

b The RFFP-II reliance on pre-1972 agent use statistics also is not relevant to current generation actual crash site conditions. Data reported by Hewes (Reference 38) on 34 LFA crash-fire incidents that occurred between 1978 and 1994, indicates that, on average, 3.03-times more agent has been used for all fire extinguishment requirements, as is required by the TCA/PCA-based approach outlined in NFPA 403.

c Actual crash data tend to substantiate the observation that the actual fire area is less than the TCA. This is to be expected, since actual crashes or ground-initiated incidents occur on sloped pavements or ground surfaces. Released fuel will spread out and flow to the low points of the surrounding terrain according to the horizontal gradients of the surface and/or the slope and permeability of surrounding soil. Data from three recent Air Force ground-initiated LFA fires (Barksdale DC-10, Kelly B-52 & Pease KC-135) indicate the actual fire area was 42%, 58% and 43%, respectively, of the TCA for each aircraft, for an average PCA/TCA relationship of 48% (Reference 1).

d The decision by the RFFP-II panel to define the PCA as 2/3 of the TCA appears to be an arbitrary decision to reduce the minimum required agent quantities and flow rates to more "affordable" levels. The use of this fire area reduction factor has not been technically challenged by the FAA or NFPA, since its inception in 1972.

(3) *Impacts on NFPA 403 TCA/PCA Methodology To Accurately Predict Minimum Required Agent Quantities and Flow Rates.*

a Actual LFA crash/incident situations are not static and rectangularly two-dimensional, as the NFPA 403 TCA/PCA methodology would suggest. There are two additional dimensions to LFA fire scenario that are of major significance to the life safety of fuselage occupants and to the effectiveness of airport fire department suppression and extinguishment operations. They are:

- The 3-dimensionality of most LFA fuel fires. Fuel or hydraulic fluid from crash-damaged lines or malfunctioning fuel distribution equipment flows through dry bay compartments and/or external openings from an elevated position onboard the aircraft to the ground surface below. This creates a fire area that is continuously replenished and susceptible to reignition from hot metal surfaces both on the aircraft and on metal debris located within or near the fire area.

- The element of time. A 3-dimensional, running fuel fire cannot be extinguished effectively with a 2-dimensional agent, such as AFFF. Therefore, crash/incident-induced fire pool fire on the ground may continuously replenish itself, and require constant agent application just for control. Additionally, fire conditions inside aircraft dry bays or involving fuel cell impingement, may generate additional flowing fuel sources, fuel cell or dry bay explosions, or both.

b The 2/3 factor applied to the TCA to reduce its size to the PCA value simply defines an assumed fire area that must be controlled. It has no physical or statistical relationship to the actual size of a "generalized" LFA fire, the relative extinguishment of the fire fighting agent to be applied (AFFF) or the length of time it will take to first control the fire and then to extinguish it. In reality, a PCA fire that is constantly resupplied by a 3-dimensional flowing fuel column, generally, will require far more agent for control than will a static pool fire that is the size of the TCA, and may be impossible to extinguish with any flow rate of AFFF.

f. Required Minimum AFFF Application Rate, 0.13 Gallons Per Minute Per Square Foot of Fire area (GPM/SF)

(1) *Analytical/Technical Basis.* Established by the RFFP-II Panel by comparison with the application rate for protein foam (0.2 GPM/SF). According to Reference 25, "the ratio between the application rate of AFFF and that for protein foam should be the same as the ratio agreed upon between the amounts of water to be provided for the two types of foam" to extinguish the same fire area. A comparative analysis of both foams was conducted that considered fire control times, extinguishment times, foam blanket stability, terrain effects, streaming range and other factors. Laboratory and live fire test data available to the Panel indicated that AFFF was more effective based on all areas in the ratio of about 3 to 2. Therefore, the Panel established the application flow rate for AFFF to be 2/3 that of protein foam, or 2/3 X 0.20 GPM/SF = 0.13 GPM/SF.

(2) *Relevance to Actual Crash Site Conditions or Recent Live Fire Experimental Data.* Minimal.

<u>a</u> FAA static pool fire tests (Reference 7) indicate that AFFF is effective for application rates as low as from 0.049 to 0.079 GPM/SF, but required longer application times for extinguishment. These tests were conducted on "ideal" flat surfaces, and the fuel was floated on water. This generated an continuous fuel surface which was effectively sealed by the AFFF.

<u>b</u> Further FAA tests (Reference 7) validated 0.13 GPM/SF as an effective AFFF "design" flow rate to gain control of large static pool fires in 1 minute or less. The same reference reports that "application rates in excess of 0.15 GPM/SF would not theoretically provide an improved fire fighting capability.".

<u>c</u> Actual crash site conditions involve discontinuous areas of ponded fuel on sloped and irregular surfaces comprised of pavement and surrounding soil conditions. Ice and/or snow also may be present. The presence of debris within the fire area serves as a source of continuous vapor reignition, once the AFFF seal is broken, and as the means to trap fuel and fire, so that it cannot be extinguished by the surrounding agent. The fire area may be continuously replenished by a flowing fuel column from the aircraft's damaged fuel system.

<u>d</u> The realistic crash site parameters of 3-dimensional fuel fires, 3-dimensional fuel surfaces, and various sloped pavement, sod or soil surfaces were not experimentally addressed by the RFFP-II Panel in 1972 when they established the minimum AFFF flow rate. Therefore, the

0.13 GPM/SF standard has only been experimentally validated for the flat, static pool fire extinguishment conditions of the FAA test programs cited, and not for actual crash site conditions.

(3) *Impacts on NFPA 403 TCA/PCA Methodology To Accurately Predict Minimum Required Agent Quantities and Flow Rates.*

<u>a</u> 0.13 GPM/SF is a reasonable "design" AFFF application flow rate. At lower application rates, extinguishment times for equal fire areas can be expected to increase. At an increased rate beyond 0.15 GPM/SF, no measurable reduction in extinguishment time for equal fire areas can be measured.

<u>b</u> This AFFF application rate does not account for the increased degree of difficulty required for the extinguishment of 2-dimensional fires on sloped, discontinuous surfaces with debris, as compared to the static, continuous surface pool fires that comprised the FAA experimental programs. There have been no experimental programs to determine the required AFFF flow rate for these actual crash site variable conditions.

<u>c</u> AFFF is not an effective primary agent for extinguishing 3-dimensional running fuel fires that often occur in LFA crash/fire incidents. Such fires are caused by fuel system malfunctions and by crash damage to fuel cells and distribution lines. Fuel can be expelled for long periods of time to continuously replenish the pool fire area, below.

<u>d</u> The use of 0.13 GPM/SF in the TCA/PCA methodology for determining minimum agent volumes cannot be expected to accurately estimate the actual GPM/SF flow rate required for actual 2- and 3-dimensional fire control and extinguishment on every square foot of every fire area.

g. Time To Achieve Initial Control Of A Fire Area Equal To 90 % of the PCA = 1 Minute

(1) *Analytical/Technical Basis.*

<u>a</u> A 60-second control time for a large (10,000 SF+) jet fuel static fire using an AFFF agent flow rate of 0.13 GPM/SF is well founded in FAA and Air Force test data, airport fire department experience and aircraft crash incident reports. NFPA 403, Appendix A, cites the following sources for a 1-minute control time: "Information from reliable large-scale fire tests, empirical data from a wide variety of sources, and field experience worldwide".

b RFFP-II data available in the 1972 era, were, principally, derived from the FAA's test program, Reference 23. Extinguishment tests included large jet fuel fires on flat concrete or ponded water surfaces. TCA-equivalent fire sizes were in the 10,000 to 20,000 SF range. More recent FAA and Air Force live fire test programs have been conducted on ponded water surfaces to minimize the environmental impact of agent and fuel contamination of test site soil and ground water sources.

(2) *Relevance to Actual Crash Site Conditions or Recent Live Fire Experimental Data.*

a Large fire control time test data are relevant only to the test site conditions from which the data were derived. These are:

- Flat, unobstructed, 2-dimensional fuel surfaces.

- The absence of a 3-dimensional flowing fuel column, or any other fuel replenishment source.

b Actual LFA crash or ground-initiated incident site conditions include:

- Sloped, irregular fuel surfaces, such as sod, sand, ice, snow, concrete & asphalt.
- Flowing/dripping fuel from one or more sources and locations to constantly replenish the ground fuel supply.
- A 3-dimensional fire column from the ground fuel pool to an elevated area of the aircraft wing, fuselage or engine nacelle where the fuel exits the aircraft structure.
- An actual or potential internal dry bay fire associated with the 3-dimensional flow of fuel from a damaged fuel line/cell to the point (s) of exit from the structure to the ground below.
- Hot metal surfaces for fuel vapor reignition associated with fire-exposed crash debris and aircraft surfaces.

c In general, the NFPA 403 1-minute PCA fire control time estimate has no experimental basis founded on the evaluation of realistic crash site pavement/ground surface conditions, or the three-dimensionality of most LFA fuel fire conditions.

(3) *Impacts on NFPA 403 TCA/PCA Methodology To Accurately Predict Minimum Required Agent Quantities and Flow Rates.*

a The 1-minute initial control time for agent application is an experimentally-validated component of the overall TCA/PCA methodology for determining minimum airport agent quantities. However, the conditions of these experiments were flat pool fires on water or concrete surfaces. These conditions, normally, are not present at actual LFA crash sites where flowing fuel impacts sloped sod, soil, sand, snow, ice and pavement surfaces, and crash debris and irregular ground surfaces may impede or prevent agent spread across the full fuel surface. Therefore, at best, a 1-minute control time for all fires is a very optimistic assumption, and has no true relevance to actual LFA crash conditions. There is no discussion in the NFPA Appendix A commentary on the effects of crash site pavement or ground conditions on the capability for initial control in 1-minute. Of course, any increase in the initial control time factor would result in a direct increase in required agent volume. This may explain why such action has not been considered.

b The initial size of the pool fire associated with a LFA incident is not, necessarily, proportional to the size of the aircraft involved. It is proportional to the flow rate of the fuel leak from the aircraft, the location (s) and mechanisms of that leak or leaks, the ground/pavement surface conditions below the leak source (s), and the geometry and slope of those surfaces. Thus, the initial fire size of a DC-9 engine fire from a broken fuel line may be very similar in size to a DC-10 LFA engine fire from the same cause, if it lands on the same pavement site conditions. On the other hand, if the fuel surface for one incident is relatively flat concrete and the other is sloped, sandy infield, there should be a great deal of difference between pool fire sizes for equal fuel flow rates.

c AFFF extinguishment effectiveness also will vary, depending on the ponded fuel surface characteristics. Fuel on pavement produces a relatively continuous surface area upon which AFFF works very efficiently. On the other hand, sloped, grassy areas produce “peaks and valleys” that will impede the continuity of agent spread and create fire pockets that the agent cannot extinguish by application and spread alone.

Additional agent will need to be delivered directly on these pockets for extinguishment. Such actions will require additional time for agent application and result in more volume being applied, as compared to an equal fire area on a flat, hard surface. Such conditions are not explicitly factored in to the NFPA 403 1-minute initial fire control time.

d In short, the NFPA 403 assumed 1-minute initial fire control time may or may not be sufficient to deal with actual LFA crash site conditions. By itself, it has no relevance to actual fuel flow or fuel pond site conditions, and cannot be expected to accurately predict required agent quantities.

h. Q_1 = Agent Volume Required To Achieve Initial PCA Fire Control = (0.13 GPM/SF AFFF Flow Rate) X 1-Minute

(1) *Analytical/Technical Basis.*

Both components of this relationship, a 0.13 GPM/SF flow rate for AFFF and a 1-minute agent application time, have been experimentally validated in FAA-conducted live fire test programs. Both are approximations. Depending on the fire site conditions, AFFF has been demonstrated to be effective at flow rates less than 0.13 GPM/SF, and 1 minute may or may not be a sufficient time to gain initial fire knockdown and control.

(2) *Relevance to Actual Crash Site Conditions or Recent Live Fire Experimental Data.*

The results of the Q_1 calculation are relevant only to the specific test conditions upon which they were validated. Q_1 may or may not predict actual agent requirements for a LFA crash/fire incident situation. As discussed in detail, above, the major determining factors are the post-crash flowing fuel rate, the surface condition of the fuel pond, and the slope and geometry of the fuel surface (s).

(3) *Impacts on NFPA 403 TCA/PCA Methodology To Accurately Predict Minimum Required Agent Quantities and Flow Rates.*

This relationship cannot be expected to accurately predict actual required agent quantities for every category of LFA crash/fire incident. It merely estimates a quantity of agent than can be reliably expected to extinguish a PCA-sized fire in 1-minute or less, provided the PCA fire is on a flat surface, no 3-dimensional flowing fuel condition exists, and AFFF is applied at 0.13 GPM/SF.

i. Q_2 = Agent Volume Required To Maintain PCA Fire Control Until Aircraft Egress And/Or Rescue Are Complete, And/Or Reinforcements Arrive = (0.13 GPM/SF AFFF Flow Rate) X 1.7-Minutes

(1) *Analytical/Technical Basis.*

a The first component of this relationship, a 0.13 GPM/SF flow rate for AFFF, has been experimentally validated in FAA-conducted live fire test programs, as discussed above. It is an approximation. Depending on the fire site conditions, AFFF has been demonstrated to be effective at flow rates less than 0.13 GPM/SF.

b The second component, a 1.7 minute AFFF application time, is an arbitrary time that is geared more to limiting the total required agent volume to an "affordable" quantity, than to any validated estimate of total agent requirements for sustained fire control or extinguishment. Appendix A to NFPA 403 states that the RFFP-II Panel "concluded that the amount of water required for Q_2 could not be calculated exactly, as it depended on a number of variables. Those variables considered of primary importance by the Panel were:

- Maximum gross weight,
- Maximum passenger capacity,
- Maximum fuel load, and
- Previous experience (analysis of aircraft rescue and fire fighting operations).

c These factors were used by RFFP-II to generate values for each airport category where $Q_2 = f \times Q_1$. The values of *f* ranged from 3 percent (103%) for Category 1 airports to 170 percent for Category 8 airports." The current NFPA 403 for *f* has been reduced to 152 percent for Airport Category 8. It is 170 percent for Airport Category 9, which includes B-747 sized LFA.

(2) *Relevance to Actual Crash Site Conditions or Recent Live Fire Experimental Data.*

None. Crash fire area and resulting required agent quantities are primarily influenced by the post-crash flowing fuel rate, the number and location (s) of flowing fuel conditions, the surface condition of the fuel pond, and the slope and geometry of the fuel surface (s). The NFPA 403-specified factors for determining the Q_2 volume of agent, i.e., maximum gross weight, passenger capacity, and fuel load, have little or no impact on fire size. These factors do have a significant impact on the degree of difficulty associated with fire control and extinguishment and fire/rescue workloads, tactics and priorities, however, there have been no experimental programs conducted in these areas.

(3) *Impacts on NFPA 403 TCA/PCA Methodology To Accurately Predict Minimum Required Agent Quantities and Flow Rates.*

a This relationship cannot be expected to accurately predict actual required agent quantities for every category of LFA crash/fire incident. It merely estimates a quantity of agent than can be reliably expected to control or extinguish a PCA-sized fire in 1.7 minutes or less, provided the PCA fire is on a flat surface, no 3-dimensional flowing fuel condition exists, and AFFF is applied at 0.13 GPM/SF.

b Data provided by Hewes (Reference 38) on the quantities of agents discharged to extinguish 34 major aircraft fires from January 1978 to January 1994, indicate that airport fire fighters used 3-times the amount of agent specified in NFPA. Exact data are not available to determine specific agent quantities used for initial control, sustained control until rescue is complete, and for final extinguishment and overhaul. However, these data clearly indicate that the NFPA 403 TCA/PCA methodology-generated agent quantities underestimate actual crash site live fire requirements.

j. Flow Rate For Hand Line Extinguishment Of Interior Aircraft Fires = 250 GPM.

(1) *Analytical/Technical Basis.*

Appendix A of NFPA 403 states that the quantities of agent, Q_3, required for combating an interior aircraft fire are "based on accepted water flow requirements for the type of fire fighting operations to be experienced....". For NFPA Airport Categories 8 - 10, this agent flow rate value is 250 GPM. No technical or experimental references are cited. Conversationally, Hewes (Reference 39) states that 250 GPM is the sum of two 125 GPM hand lines drawn from fire response vehicles at the incident site, and represents the maximum flow rate that could be effectively applied by two fire fighters in a cabin fire fighting situation.

(2) *Relevance to Actual Crash Site Conditions or Recent Live Fire Experimental Data.*

None. Agent flow rate requirements (GPM) have not been experimentally or analytically determined from representations of actual crash site fuel flow, interior cabin combustibles and/or interior cabin fire conditions.

(3) *Impacts on NFPA 403 TCA/PCA Methodology To Accurately Predict Minimum Required Agent Quantities and Flow Rates.*

a The results of the NFPA 403 LFA calculation for Q_3 are based on a 250 GPM flow rate for agent. These are no data or references to substantiate that this flow rate is the minimum, optimum or maximum flow rate for LFA interior fire fighting.

b 250 GPM may or may not be a sufficient agent flow rate to deal with LFA interior fires. More importantly, AFFF, which is carried on board Air Force crash vehicles, may not be the most effective agent to be applied to the Class A, B & C fires that, normally, might be expected to be involved in the interior of a LFA crash or ground fire incident. Deep-seated, electrical, fuel or hydraulic fluid-fueled fires that may be oxygen-enriched, as well as large fire areas involving typical cabin combustibles (seats, compartment partitions, baggage, etc.) can be expected.

c AFFF is not well suited for 3-dimensional or deep-seated fires cabin fires or for interior combustible fires. It is primarily used against large pool fires on pavements or ground surfaces.

d The NFPA 403 implicit assumption for Q_3 is that this quantity of agent will be effective for all LFA interior fires, if a 250 GPM flow rate is provided for 10 minutes. This is both misleading and non-conservative. Recent Air Force experience (Reference 1) is that AFFF has been very ineffective in controlling or extinguishing LFA interior fires. Therefore, a 250 GPM flow rate for AFFF or water may be of little relevance for many LFA interior fire fighting scenarios.

k. Agent Flow Rate Duration For Hand Line Extinguishment Of Interior Aircraft Fires = 10 Minutes

(1) *Analytical/Technical Basis.*

None. This is an arbitrary agent application time established by the NFPA 403 Technical Committee. There are no cited references.

(2) *Relevance to Actual Crash Site Conditions or Recent Live Fire Experimental Data.*

None. Application of agent via hand lines at a combined 250 GPM flow rate for 10 minutes during interior LFA fire fighting operations may or may not extinguish all classes of fires in all interior fire areas.

(3) *Impacts on NFPA 403 TCA/PCA Methodology To Accurately Predict Minimum Required Agent Quantities and Flow Rates.*

The results of the NFPA 403 calculation for Q_3 are based on a 250 GPM flow rate for agent for a 10-minute time period. These are no data or references to substantiate that the 10-minute duration of agent application or the total agent quantity that is calculated are the minimum, optimum or maximum flow rate and agent volume for LFA interior fire fighting.

1. Required Agent Quantity For Hand Line Extinguishment Of Interior Aircraft Fires = Q_3 = 250 GPM X 10 Minutes

(1) *Analytical/Technical Basis.*

None, as above.

(2) *Relevance to Actual Crash Site Conditions or Recent Live Fire Experimental Data.*

None, as above.

(3) *Impacts on NFPA 403 TCA/PCA Methodology To Accurately Predict Minimum Required Agent Quantities and Flow Rates.*

The results of the NFPA 403 calculation for Q_3 are based on a 250 GPM flow rate for agent for a 10-minute time period. There are no data or references to substantiate that the 250 GPM flow rate or the 10-minute duration of agent application are the minimum, optimum or maximum values for these factors. Furthermore, there are no experimental data on the fire extinguishment effectiveness of AFFF versus typical interior aircraft fire sources and locations. Therefore, the total agent volume for LFA interior fire fighting computed by this methodology, Q_3, and the effectiveness of this quantity are without substantiation, and cannot be expected to accurately predict crash site requirements or agent performance effectiveness.

SECTION V

IMPACT OF CURRENT TECHNOLOGY AIRCRAFT AND FIRE SUPPRESSION AGENTS AND EQUIPMENT ON AIRPORT FIRE DEPARTMENT CRASH-RESCUE CAPABILITIES

A. GENERAL

A review was conducted of the current aircraft and fire suppression agent and equipment technologies to identify potential impacts on fire department ARFF capability. Certain aircraft and aircraft system technological developments have created an increased challenge to fire fighters. At the same time, improved CFR vehicle control and delivery systems, as well as improved fire fighting agents and combinations of agents, are available. These technologies can provide fire fighters an increased ability to cope with future LFA fire fighting challenges.

B. AIRCRAFT/AIRCRAFT SYSTEM FACTORS

1. Aircraft Size

a. Discussion

The size of aircraft has consistently increased over the years to create internal and external hard to reach areas for firefighters that are both time consuming and labor intensive to access. For example, the C-5A is 247 feet long and over three stories high, and the KC-10 is over 181 feet long and 58 feet high. Existing Air Force agent delivery equipment is not adequate to effectively reach fires in high nacelles, crew or payload areas or inside internal wing and fuselage dry bays.

b. Recommendation

Articulated/telescoping booms with high velocity, skin-penetrating nozzles are needed to improve agent delivery and cavity-penetration capabilities. This equipment is available and should be tested.

2. Compartmentization

a. Discussion

Large interior compartments in aircraft pose a similar problem for fire fighters. The C-5A aircraft has several interior compartments totaling approximately 42,000 cubic feet of space. Similarly, the 747 has over 30,000 cubic feet of space. In addition, aircraft interiors are made up of multiple combustibles (electronics, hydraulic fluids, insulating material, oxygen supplies and other class

A, B, C & D materials). This can lead to 3-D, oxygen-enriched and deep-seated fires, which are not effectively extinguished by AFFF.

b. Recommendation

Effective, 3-dimensional agents and agent combinations should be tested under realistic LFA interior fire conditions.

3. Aircraft Fuels

a. Discussion

(1) There has been no definitive study regarding JP-4/8 fuels as they pertain to fire fighting agent performance. The amount of fuel on LFA can exceed 50,000 gallons and can pose a special threat to fire fighters when exposed to a fire. Therefore, no real-world data is available to assess the impact of the USAF's conversion from JP-4 to JP-8 on fire suppression requirements.

(2) Based on a flash point -10 $^{\circ}$F to +30 $^{\circ}$F for JP-4 and of +95 $^{\circ}$F to +145 $^{\circ}$F for JP-8, we know that JP-4 ignites easier. Conversely, once ignited, we know JP-8 burns hotter and more intensely. Higher JP-8 burning temperatures create an increased hazard and operational threat to fire fighters.

(3) There are voids (dry bay areas) around aircraft fuel tanks which can host hard to reach fires during an LFA fire incident. JP-8 fire growth and decay, and agent performance in these areas are unknowns.

b. Recommendation

Tests should be conducted to identify the relative extinguishment performance of 2- and 3-dimensional agents versus JP-4 and JP-8. Since all recent Air Force LFA fire fighting has been with JP-4 fuel fires, test data can be used to identify differences in agent application and fire control techniques needed for JP-8. Tests should include evaluations of agent penetration and fire extinguishment in confined, hard to reach areas.

4. Aircraft Materials

a. Discussion

(1) Aircraft metals and alloys have a broad range of melting points and in some cases pose a toxicological hazard for fire fighters. The high temperatures created by these materials serve as a point of

ignition/reignition for other combustibles, fuels and hydraulic fluids.

(2) Composite materials in existing and next generation aircraft are extremely sensitive to flame impingement. Delamination begins in approximately 20 seconds following full fire involvement, and extremely toxic combustion products are produced. Fire spread characteristics and structural weakening parameters of composite materials involved in high-percentage composite LFA (B-2/C-17) fires are unknowns.

b. Recommendation

The impact of composite materials and ultra-high strength metal alloys on fire spread, agent performance, and toxic combustion products generation should be examined by live fire experiments.

C. FIRE FIGHTING AGENTS

1. Discussion

a. Fire fighting agents commonly used over the past 20 years include aqueous film forming foam (AFFF), fluoroprotein foam, dry chemicals and halogenated (Halon 1211 & 1301) agents. Halon 1211, considered a clean agent, has been used, primarily, on ground-initiated aircraft engine, brake and enclosed compartment fires. This agent is being phased out because of its ozone-depleting properties, and no clean agent replacement is presently identified.

b. Since the mid-1970s, military and commercial airport fire departments in the United States have used AFFF as the primary ARFF agent.

c. Dry chemical has been used by Air Force and commercial fire departments as an auxiliary agent, alone; and in conjunction with Halon 1211 for small hydrocarbon fires in their incipient stage. The agent, although effective, was considered hard to clean up after use and extremely corrosive to aircraft engines. Consequently, it has not been used as a primary agent during large scale LFA flight line or crash/fire incident. Dry chemical agent has had considerable success as a primary agent in West Germany.

2. Finding

AFFF is not an effective primary agent for the control and extinguishment of LFA crash/fire incidents. Literature review data and recent Air Force live fire test results indicate that dry chemical agents and a combination agent consisting of dry chemical and a foam agent should produce much better overall fire extinguishment performance for LFA crash site conditions and aircraft configurations. The technical literature documents dry chemical agent very powerful, 2- and 3-dimensional fire extinguishing agent.

3. Recommendation

Dry chemical and dry chemical/foam combination agents should be tested under realistic LFA crash site conditions to establish their 2- and 3-dimensional, and interior firefighting effectiveness versus AFFF.

D. FIRE VEHICLES/EQUIPMENT

1. Vehicle Agent Control Systems

a. Discussion

Fire fighting agent control systems within the cab of a CFR vehicle are critical to effective agent application, and, consequently to the control and extinguishment of the fire. Mandatory required capabilities include the ability to properly move the turret, to change agents/agent streams, to open and close the turret, and to accurately determine and maintain target range and sweep requirements. Where feasible, CFR vehicle turret controls should be based on ergonomically-based, single hand, eye-level aiming and flow control systems.

b. Recommendation

Improved systems are available and should be tested. Existing Air Force fire fighting control system ergonomics do not provide maximum aiming accuracy.

2. Fire Fighting Primary Agent Delivery Systems

a. Discussion

Existing Air Force CFR vehicle water/AFFF delivery systems have remained the same over the past 20 years. New systems that have the potential for improving ARFF effectiveness are available. These include:

- A system for simultaneous foam and dry chemical delivery. It shows significant promise for extinguishing exterior/interior, deep-seated and 3-D fires.

- Compressed gas technology to increase agent throw range and accuracy (GPM/SF on target) from CFR roof turrets.

b. Recommendation

These technologies should be tested and evaluated under realistic LFA crash sire conditions to determine their capabilities versus AFFF to control and suppress 2- and 3-dimensional LFA exterior and interior fires.

SECTION VI

LFA FIRE FIGHTING LIVE FIRE VALIDATION TEST PROGRAM

A. BASIS OF THE REQUIREMENT

1. Analysis results indicate that the NFPA 403 TCA/PCA methodology for determining minimum agent quantities and flow rates was not developed on a sound technical or experimental basis. The TCA/PCA equation has been demonstrated to consistently underestimate actual agent application times and gallonage requirements by a significant margin. Additionally, recent crash site statistics demonstrate that NFPA 403-specified primary agents and most current inventory agent delivery systems are inadequate for effective ARFF operations.

2. A large-scale, live fire test program is required to validate analysis results and to experimentally determine realistic values for critical fire fighting parameters, agents and agent delivery systems that can have a major impact on LFA ARFF operational success or failure. Tests must be aimed at improving the NFPA methodology for determining agent requirements and at identifying improved airport fire fighting agent and apparatus capabilities.

B. TEST PROGRAM OBJECTIVES

1. Compare assumed NFPA 403 primary foam agent 2-dimensional performance to actual 2-dimensional performance. Tests fires will conducted on realistic airport surfaces.

2. Compare assumed NFPA 403 primary foam agent 2-dimensional performance to actual performance against 3-dimensional fires. Test fires will be conducted with running fuel conditions that flow to realistic airport surfaces.

3. Compare AFFF primary foam agent 2- and 3-dimensional performance, as determined by the above two test fire scenarios, to the performance of dry chemical agent and hydrochem agent (AFFF + dry chemical mixture) under the same fire and pavement surface conditions.

4. Compare assumed NFPA 403 primary foam agent performance to actual performance versus realistic LFA cabin material fires.

5. Compare AFFF primary foam agent interior cabin fire performance to the performance of dry chemical agent and hydrochem agent (AFFF + dry chemical mixture) under the same fire conditions.

6. Determine the relative extinguishment performance of AFFF, dry chemical agent and hydrochem versus realistic, 3-dimensional, LFA fire scenarios involving high, hard to reach fire areas and interior cabin fires.

7. Determine the capability of new technology agent delivery equipment and control systems to improve airport fire fighter capability versus realistic, 3-dimensional, LFA fire scenarios involving high, hard to reach fire areas and interior cabin fires.

C. LFA LIVE FIRE TEST PROGRAM MATRIX

Table VI-1 details the proposed live fire test program to validate NFPA 403 TCA/PCA deficiencies and to evaluate improved LFA firefighting agents and delivery apparatus. All tests will be conducted at the Fire Research Laboratory's environmentally-safe live fire test facility that is located at Tyndall AFB, FL. Figure VI-1 shows a plan view of the test facility and LFA mockup. Figure VI-2 shows an elevation of the LFA mockup components. Video documentation of all test events will be conducted.

Table VI-1. LFA Live Fire Test Program Matrix (Page 1 Of 2)

	TEST EVENT REPLICATIONS								
Test Event Description	**JP-8 AFFF**	**JP-8 Hydro**	**JP-8 DryCh**	**JP-8 Total**	**JP-4 AFFF**	**JP-4 Hydro**	**JP-4 DryCh**	**JP-4 Total**	**Test Total**
Static Pool Fire (900 SF) Agent Application Calibration Tests:									
Concrete + Obstructions					5	5	5	15	15
Static Pool Fire (900SF) Tests: Extinguisher Delivery									
1. Water + Obstructions	3			3	3			3	6
2. Concrete + Obstructions	3	3	3	9	3	3	3	9	18
3. Sod + Obstructions	3			3	3			3	6
3-D Flowing Fuel Fire (900 SF) Agent Application Calibration Tests:									
Concrete + Obstructions					5	5	5	15	15
3-D Flowing Fuel Fire (900SF) Tests: Extinguisher Delivery									
1. Water + Obstructions	3			3	3			3	6
2. Concrete + Obstructions	3	3	3	9	3	3	3	9	18
3. Sod + Obstructions	3			3	3			3	6
Large Scale CFR Equipment Performance Tests: Concrete Fire Surface									
1. P-19 (AFFF)									
a. High Wing	3			3					3
b. High Wing Heated Fuel (160 ^{O}F)	1			1					1
c. High Nacelle	3			3					3
d. Interior Cabin (Hand Line)	3			3					3
2. Penetrator Boom (AFFF)									
a. High Wing	3			3					3
b. High Nacelle	3			3					3
c. Low Nacelle	3			3					3
d. Interior Cabin	3			3					3
3. Snozzle (AFFF)									
a. High Nacelle	3			3					3
b. Pool Fire Extended Reach (Over/Across Fuselage)	3			3					3

Table VI-1. LFA Live Fire Test Program Matrix (Page 2 Of 2)

	TEST EVENT REPLICATIONS								
Test Event Description	**JP-8 AFFF**	**JP-8 Hydro**	**JP-8 DryCh**	**JP-8 Total**	**JP-4 AFFF**	**JP-4 Hydro**	**JP-4 DryCh**	**JP-4 Total**	**Test Total**
4. Hydrochem Vehicle									
a. High Wing		3		3					3
b. High Nacelle		3		3					3
c. Interior Cabin (Hand Line)		3		3					3
5. Dry Chemical Vehicle									
a. High Wing			3	3					3
b. High Nacelle			3	3					3
c. Interior Cabin (Hand Line)			3	3					3
P-19 Roof Turret Control Ergonomics Evaluation: Water Delivery/No Fire									
1. Existing Controls									3
2. Improved Controls									3
AFFF Application/Delivery Technique Evaluation Tests (AFFF): Concrete Surface With LFA Mockup Obstruction									
1. Rain Drop Delivery	3			3					3
2. Seat Of Fire Delivery	3			3					3
TEST EVENT TOTALS	52	15	15	82	28	16	16	60	148

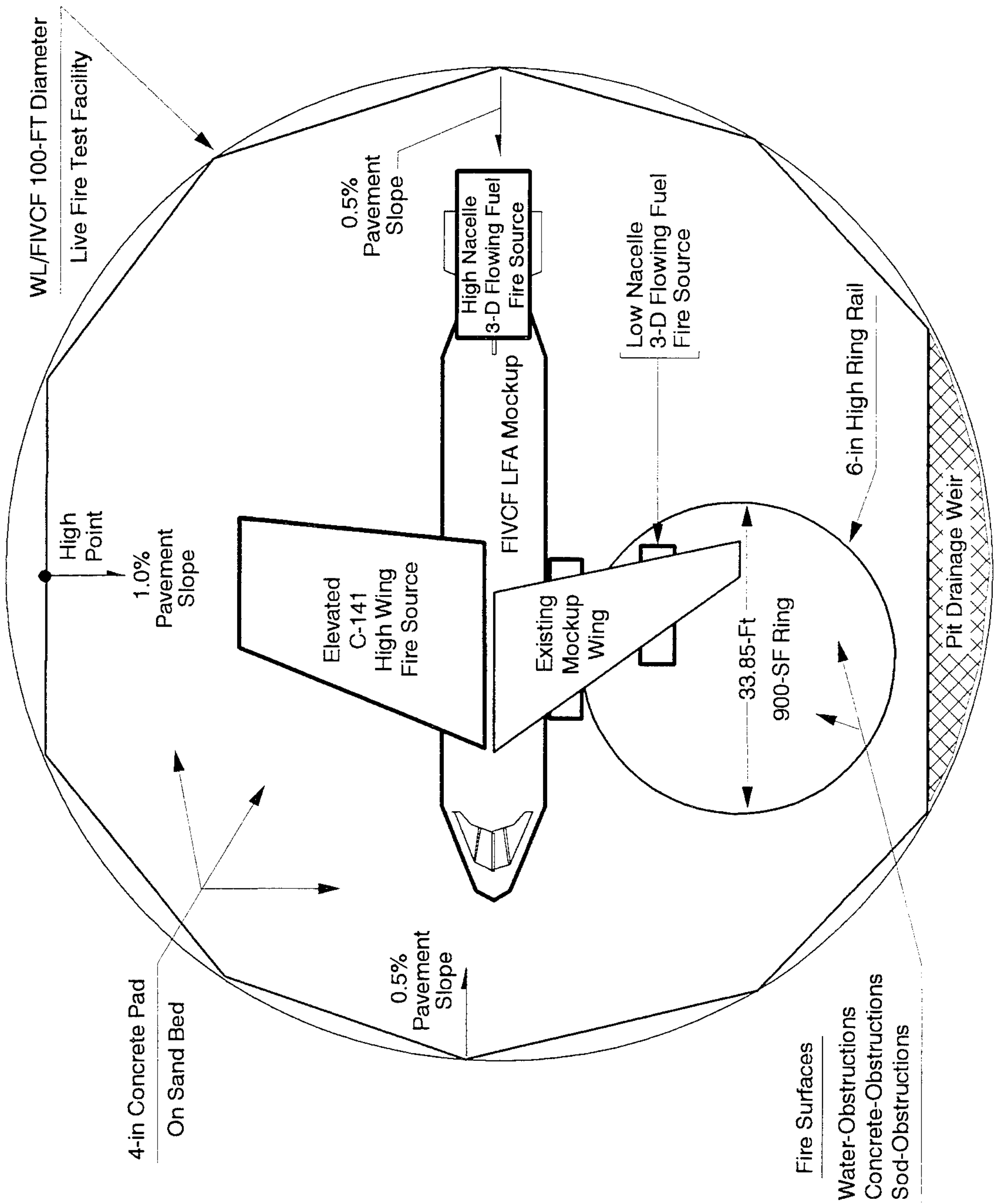

Figure VI-1. Fire Research Laboratory Live Fire Test Facility Layout

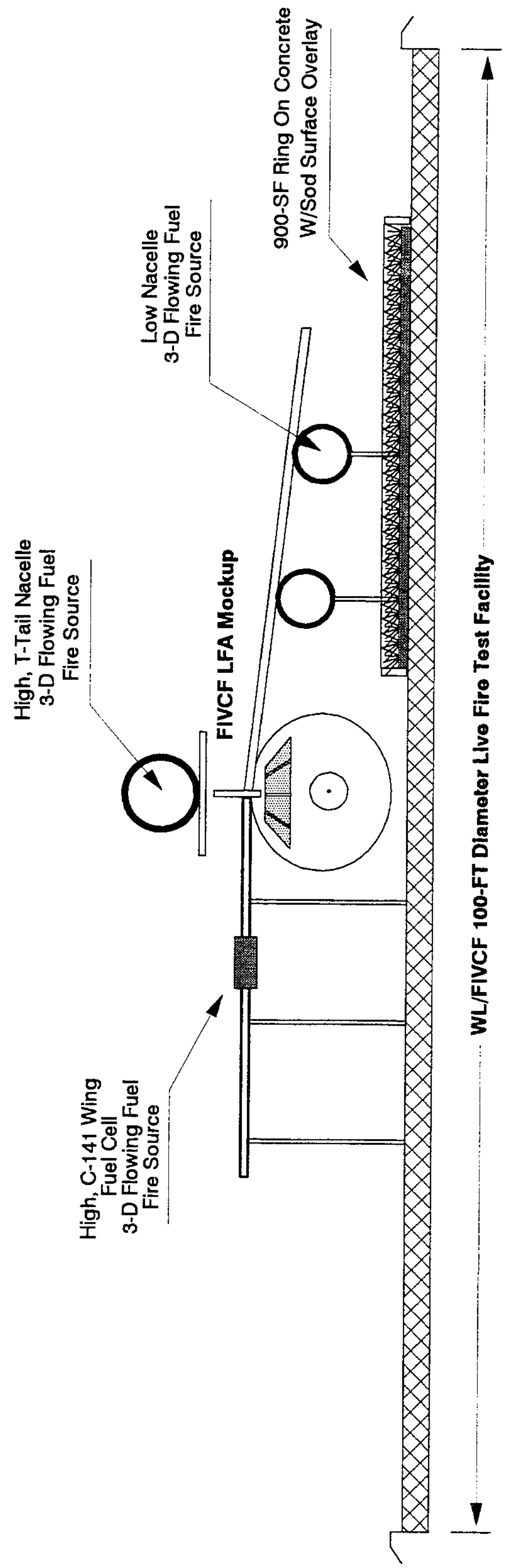

Figure VI-2. Fire Research Laboratory Live Fire Test Facility LFA Mockup Configuration

SECTION VII

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

1. The operational fire fighting experience and databases of the 1960's that contributed to a large measure of the current TCA/PCA calculational procedure did not include the on-scene experience, crash response histories and interior/exterior fire suppression statistics from modern LFA, such as the B-747, DC-10, L-1011, and Airbus A-300/340. Furthermore, experimental programs to determine agent effectiveness and minimum flow rate parameters did not reflect accurate crash site conditions or current agent performance.

a. Fire tests to determine agent performance and flow rates were conducted, primarily, using protein foam. They were conducted on "ideal" static, flat, 2-dimensional pool fire surfaces. The fuel column was floated on either on water or on a paved surface. Actual Air Force and commercial airport crash statistics since 1978 indicate the following crash site conditions:

- AFFF as the primary agent,
- 3-dimensional flowing fuel conditions from damaged fuel lines and/or fuel cells, and,
- A wide mix of sloped pavement, grass, sand, snow , ice and water crash site surfaces.

b. Test fires were limited, primarily, to the exterior area of the aircraft. Fuselage mockups were not realistic, and did not accurately account for the crash-worthiness or insulating properties of modern cabin interiors. Extinguishment of current-day interior combustible materials was not experimentally addresses.

2. The "largeness" of current inventory LFA creates difficult fire fighting and rescue problems and obstacles that were not present or identified when the original TCA/PCA methodology was being developed. These include:

a. 3-dimensional, cascading fuel or pressurized hydraulic fluid fires originating in high T-tail engine nacelles, APUs or dry bay compartments and high-wing engine nacelles, dry bays and/or fuel cells.

b. High, elevated, "hard to reach" sources of these 3-dimensional, flowing fuel fires, such as the interiors of engine nacelles, overhead wing dry bays, or APU/electronics equipment bays.

3. The crash worthiness of new generation LFA results in larger, intact, post-incident aircraft components. Each may present a separate exterior and interior fire fighting and rescue requirement, to include inverted cabin sections. Extinguishing agent requirements for fires fueled by cabin interior panels, seat/cushion materials, composite materials and other interior combustibles have not been experimentally determined.

4. A revised methodology to calculate required agent quantities for airport fire fighting and rescue is required to ensure that the Air Force maintains the fire department manpower, vehicle, agent and equipment resources necessary to provide a defined and repeatable level of fire protection at air bases supporting LFA operations.

B. CONCLUSIONS

1. The NFPA 403 TCA/PCA methodology is technically flawed. Its analytical and experimental basis does not accurately reflect LFA crash site conditions. The TCA/PCA methodology cannot accurately predict minimum agent quantities for airport fire fighting initial response or for the secured extinguishment of a major fraction of the total fire area.

2. The NFPA 403 TCA/PCA methodology does not account for the possible presence of 3-dimensional, flowing fuel fires at LFA crash sites or specify agent types and quantities to control and extinguish these fires.

3. NFPA 403 specifies primary foam agents for application to all airport crash/fire situations and aircraft sizes, including LFA. References 3 and 23 document that AFFF is not effective for the extinguishment of 3-dimensional exterior fires or for deep-seated interior cabin fires.

4. Current inventory Air Force CFR equipment is not configured to meet the agent delivery requirements of the LFA crash site. LFA fires have occurred in very high, hard to reach areas, such as high-wing dry bays, C-5A and DC-10 wing nacelles and DC-10 T-tail nacelles, and in elevated crew and payload areas.

5. Aircraft metals, metal alloys and composite materials used in new generation LFA create unique fire conditions. All present increased penetration resistance for agent application tools and equipment. Composites off-

gas extremely toxic combustion by-products, and structurally delaminate within 20 seconds of direct flame involvement.

6. The impact of the Air Force conversion from JP-4 to JP-8 has not been assessed with respect to agent performance or fire fighter operations. JP-8 burns with flame temperatures. The effect of this on factor occupant survivability has not been determined.

C. RECOMMENDATIONS

1. The Fire Protection Group (WL/FIVCF) should conduct a large scale, live fire experimental program to provide the technical basis for more accurately predicting Air Force vehicle and agent requirements for LFA fire fighting. Test results should be used to:

a. Estimate the margin of error of the NFPA 403 TCA/PCA methodology for predicting primary foam agent performance on realistic crash site surfaces.

b. Estimate the margin of error of the NFPA 403 TCA/PCA methodology for predicting primary foam agent performance against 3-dimensional, flowing fuel fires under realistic LFA crash site conditions and surfaces.

c. Compare the 3-dimensional fire extinguishment performance of AFFF, hydrochem and dry chemical powder agents under realistic LFA crash site conditions and surfaces.

d. Determine the optimum agent(s) for use against LFA crash/fires in high, hard to reach, engine nacelle, interior dry bay and cabin areas.

e. Determine the optimum agent delivery system (s) for use against LFA crash/fires in high, hard to reach, engine nacelle, interior dry bay and cabin areas.

f. Determine the impact of JP-8 fuel fires on agent performance and fire fighter operational effectiveness.

2. The Air Force should use analyses and live fire test results to revise TA 012 direction for agent types, CFR vehicle configurations and special apparatus to conduct LFA fire fighting and rescue operations.

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